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16. ABSTRACT

Heat flux data from the USEPA Regional Air Pollution Study in St. Louis are presented. Large spatial variations exist on both a land use scale and the urban scale. The analyses of these data includes an examination of the fetch requirements for representative eddy correlation measurements of heat flux in an urban environment. It is shown that heat flux representative of an upwind fetch, ℓ_x, requires a minimum observation height proportional to $\ell_x^{3/4}$. The role of advection on both the urban and sub-urban or land use scale is also explored. The data clearly indicates advection can strongly modulate and can even dominate the vertical heat flux above surfaces in areas where large temperature gradients exist. The advection contribution is biased positive for cold air advection and negative for warm air advection and may result from either the urban heat island or sub-urban mesoscale features. Furthermore, the depth of advection influence is shown to be proportional to the horizontal scale of the phenomena or inversely to horizontal temperature gradient.

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JOURNAL ARTICLE

MODULATION OF HEAT FLUX BY DIFFERENT SCALES OF ADVECTION IN AN URBAN ENVIRONMENT

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Abstract. Sensible heat flux data obtained from the U.S. Environmental Protection Agency's Regional Air Pollution Study in St. Louis, Missouri are presented and discussed. Large spatial variations exist in heat flux on both a land-use scale and the urban scale. Arguments based upon empirical data and sampling theory show that estimates of heat flux representative of an upwind fetch l_x require a minimum observation height proportional to $z^{3/4}$. The influence of advection on the magnitude of the heat flux is also explored for both the urban and sub-urban or land-use scales. The data clearly indicate that advection can strongly modulate and even dominate the vertical heat flux above surfaces in areas which maintain large horizontal temperature gradients. The advection contribution is positive for cold air advection and negative for warm air advection, and may result from either the urban heat island or land-use mesoscale features. The depth of advective influence is directly proportional to the horizontal scale of the phenomenon and inversely proportional to horizontal temperature gradient.

1. Introduction

Sensible heat flux, H, within an urban environment can exhibit large spatial variation, primarily because urban land-use patterns vary greatly. In turn, the mean flow field is modified resulting in an urban heat-island circulation. The mean and turbulent flow fields are also constantly readjusting to local and mesoscale advection effects, thus making it difficult to define the turbulent and mean scales for urban areas.

Knowledge of the turbulent scales and scale interactions resulting from complex urban land-use patterns is necessary for urban air quality modeling, as well as for climatological studies. Heat flux is an important parameter in describing dispersion in unstable conditions (see Lamb, 1978; Willis and Deardorff, 1978; and Venkatram, 1980). Thus large urban spatial variability of heat flux must be acknowledged in urban modeling. This paper discusses a methodology for interpreting turbulent heat flux data. Results from the boundary-layer program of the U.S. Environmental Protection Agency's (EPA's) Regional Air Pollution Study (RAPS) (see Pooler, 1974; Schiermeier, 1978) in St. Louis, Missouri, are presented to assess the magnitude of the spatial, land-use, and diurnal variability of heat flux in an urban setting. The role of advection is discussed.

2. Theory

2.1. Representativeness of Measurements

Sensible heat flux due to turbulent motions can be measured by several methods, for example, surface energy balance, aerodynamic transfer parameterization techniques,

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vertical wind and temperature profile measurements, enthalpy budget considerations, and eddy correlation measurements. Inherent in these measurements is the requirement that there exists a distinct time or length scale for turbulence generated at the surface or induced by internal gradients. It is desirable to have horizontally homogeneous fetch upwind of a measurement site. Operationally, in an urban setting, this requirement is usually compromised. In this paper, we propose that a measurement of heat flux may be considered conditionally stationary if the time period, τ_x (or path length, l_x), of the observation contains a statistically significant number of realizations of the major heat-flux-bearing eddies, i.e., the upwind land-use areal extent, l_x, must be much larger than the representative scale of the heat eddy. This condition can be summarized as follows.

$$l_x \gg \lambda_{wT} \tag{1a}$$

and similarly

$$\tau_x \gg \tau_{wT} \tag{1b}$$

where λ_{wT} and τ_{wT} are measures of the length and time scales of the heat convective elements, respectively.

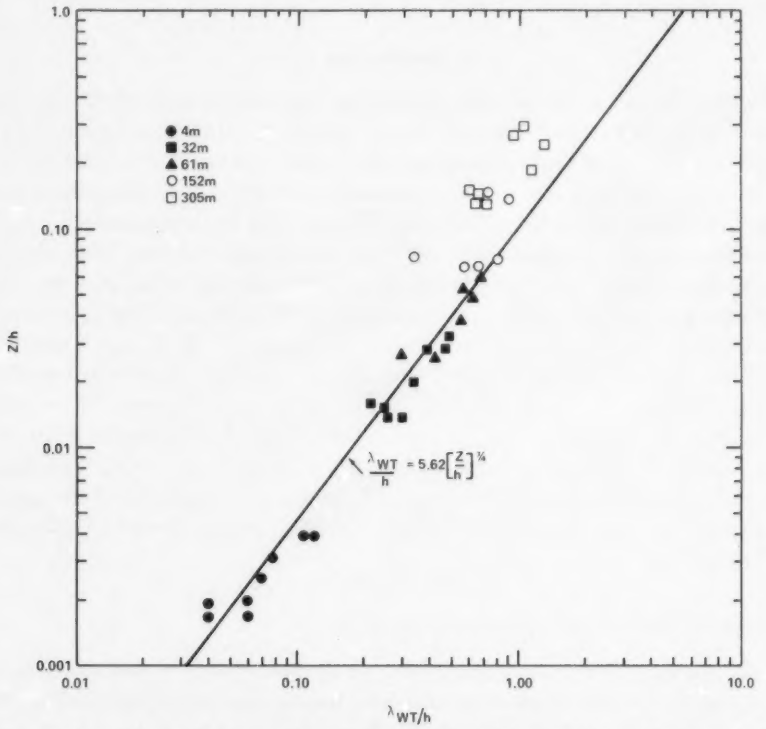

Fig. 1. Peak wavelength of wT cospectrum normalized by mixed-layer height as a function of z/h. Data from Caughey and Kaimal (1977).

Recently, cospectra of vertical velocity, w, and temperature, T, from the surface boundary layer to heights within the convective boundary layer have been reported by Caughey and Kaimal (1977). They define an eddy scale λ_{wT} for heat flux to be the peak in the wT cospectrum. They found that this scale increases with height in the surface layer, i.e., $z < 0.1h$, where z is height and h is the depth of the dry convectively mixed layer. Then λ_{wT} approaches a constant value above $z/h > 0.1$. Near the top of the mixed layer, however, no single scale can represent the processes, which must include entrainment from above. These features are shown in Caughey and Kaimal's Figure 3. This height variation has implications for the problem of interpreting heat flux data. Obviously, the higher the measurement made, the longer the required length of record and the larger the representative upwind area 'seen' in the record. A useful relationship for λ_{wT} can be obtained from the Minnesota data presented in Caughey and Kaimal (1977). The data in their Figure 3 combined with the mixed-layer heights reported in Kaimal *et al.* (1976) give the results shown in Figure 1. The ratio λ_{wT}/h increases with z/h below 0.1, which is qualitatively similar to the convective similarity results for σ_w/w^* or λ_w/h (with w^* being the convective velocity scale $(\overline{gw'T'}\ h/T)^{1/3}$). The results suggest a power law behavior

$$\frac{\lambda_{wT}}{h} = 5.62(z/h)^{3/4} \qquad 0 < z/h < 0.1 \tag{2a}$$

that approaches a limiting value somewhere between 1 and 2 for the region

$$0.1 \leq z/h \leq 0.5.$$

Thus,

$$\lambda_{wT} = az^{3/4} \tag{2b}$$

with a = 32, 35, and 38 for h = 1, 1.5, and 2 km, respectively.

These results can be inverted to indicate the height of measurement required to 'see' the scaled heat eddy. That is,

$$z = \left(\frac{\lambda_{wT}}{5.6}\right)^{4/3} h^{-1/3}. \tag{3}$$

Earlier, a minimum record length was required to contain a sufficient number of occurrences of λ_{wT} for statistical confidence. It was assumed that this 'adequate' number of realizations would be satisfied when the difference between the measured λ_{wT} and the expected or 'true/ideal' eddy scale $\bar{\lambda}_{wT}$ was no greater than its standard deviation. The required number of events, n, was obtained through the 't' distribution of statistics where

$$t = \frac{(\bar{\lambda}_{wT} - \tilde{\lambda}_{wT})}{s}(n-1)^{0.5} = \frac{D(n-1)^{0.5}}{s} \tag{4a}$$

and s is the standard deviation.

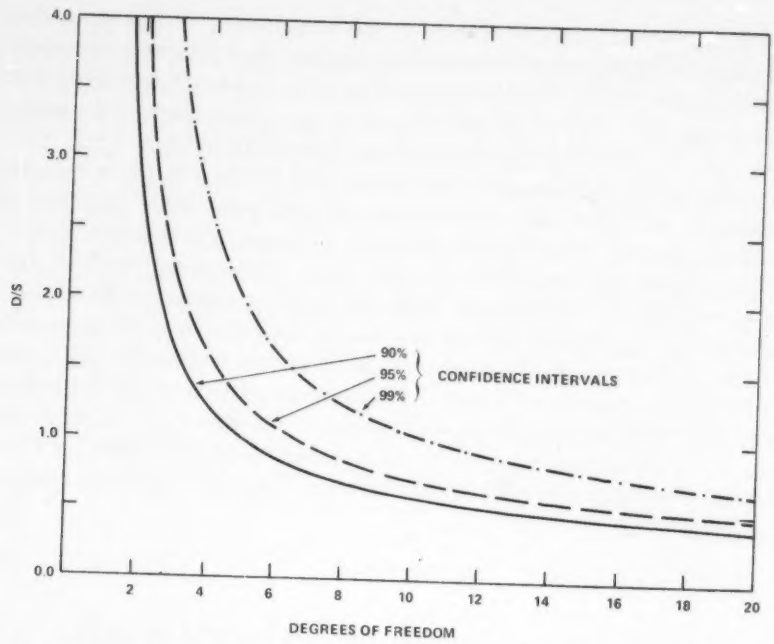

Fig. 2. Difference between the sample versus population mean normalized by the sample standard deviation as a function of degrees of freedom using the '*T*' distribution.

Thus,

$$\frac{D}{s} = t/(n-1)^{0.5}, \tag{4b}$$

The distribution of $t/(n-1)^{0.5}$ versus n is shown in Figure 2, where for $D/s = 1$, n is about 5, 7, and 11 at the 90, 95, and 99% confidence levels, respectively. Clearly, for $n < 10$, D/s increases rapidly, perhaps unacceptably; in contrast, $n > 10$ does not result in as large a decrease (viz., the law of diminishing returns). Thus, a value of $n = 10$ appears to be a reasonable compromise, i.e.,

$$l_x = n\lambda_{wT} = 10\lambda_{wT}. \tag{5}$$

The authors propose that this relationship, together with $\lambda_{wT}/h = f(z/h)$, serve as a basis for defining the minimum fetch or advective time period, $l_x/\bar{u}$, required for a measurement made at height z_m. Thus,

$$l_x = 56h^{1/4} z_m^{3/4}. \tag{6a}$$

This is shown in Figure 3 for $h = 1$, $h = 1.5$, and $h = 2$ km. Conversely,

$$z_m = 4.67 \times 10^{-3} l_x^{4/3} h^{-1/3}. \tag{6b}$$

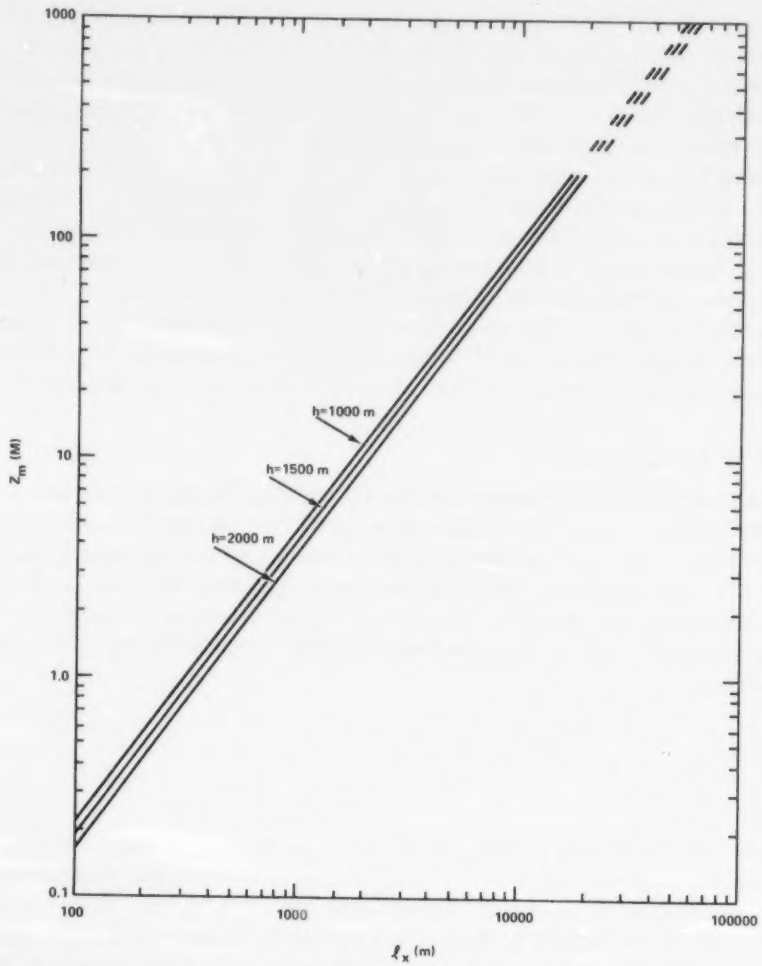

Fig. 3. Model of observation height requirements to obtain heat flux for a land-use scale of upwind fetch l_x.

Thus, z_m is to be considered the appropriate height of measurement required to obtain reliable heat flux data from a uniform upwind land-use fetch of order l_x. Equivalently, land-use scales smaller than l_x are to be considered subgrid scale and therefore not statistically resolvable for measurements made at z_m. Conservatively, this requires the cospectra of w and T to be quasi-horizontally homogeneous for a given land use. However, if large spatial inhomogeneities exist within the l_x domain, the basis for the use of Equations (2) and (6) is weakened. Note that the relationship for z_m was developed from data obtained under fairly ideal conditions. It is unlikely, however, that

urban results should depart from the ideal by much more than a factor of two. If so, D/s can be adjusted up or down depending on whether the expected value of λ_{wT}(urban)/λ_{wT}(ideal) is greater than or less than one, respectively. As seen in Figure 2, if λ_{wT}(urban) is twice or one-half that of λ_{wT}(ideal), then $n = 5$ or $n = 20$, respectively, which implies a maximum range of uncertainty in D/s of a factor of three.

Equation (6) can be interpreted as follows. Suppose one wants to determine the heat flux for a site whose upwind fetch of 2 km can be considered quasi-uniform. Measurements made at 10 m above the zero-plane displacement should adequately represent the heat flux for that area. This measurement will not relate confidently to shorter fetches. It is important to realize that the arguments leading to Equation (6) break down as z_m/h approaches 0.5 or greater. This occurs when the cospectrum between w and T includes significant negative contributions at a variety of frequencies or scales due to entrainment processes active in that region (see Kaimal *et al.*, 1976; Caughey and Kaimal, 1977).

2.2. Role of Advection

An important feedback mechanism exists between advection and surface heat flux, since heat flux output over a surface is moderated by advective influences. This process may be quite active in an urban heat island with microclimatic land-use variations that create small-scale, large-amplitude, horizontal temperature gradients superimposed on the mesoscale heat island gradients. This process can be illustrated by integrating the equation for the enthalpy change with height from the surface to the top of the mixed layer, h, i.e.,

$$\int_0^h \frac{\partial \bar{\theta}}{\partial t}\,\mathrm{d}z + \int_0^h u\frac{\partial \bar{\theta}}{\partial x}\,\mathrm{d}z = \frac{H_0 - H_h}{\rho c_p} \tag{7}$$

where u is the mean wind velocity and where terms such as the mean transport of enthalpy due to mean vertical velocity and long-wave radiative flux divergence are neglected. Typically, in horizontally homogeneous surface conditions, $\partial\bar{\theta}/\partial x = 0$, and thus the heat flux is controlled by the local heating rate. In the presence of a heat island, $\partial\theta/\partial x = 0$ only in the rural areas far upwind and downwind and at the center of the heat island. Assuming some spatial uniformity in h and a transport wind invariant with height, the advection term is positive upwind and negative downwind of the heat-island centroid. The cold air inflow requires additional heat from the surface (and from anthropogenic sources) to modify its temperature structure, i.e., to maintain the heat island. Likewise, air flowing away from the center of the heat island requires less heat (and may even give up heat to the surface since it carries with it the warmest air of the heat island). Consequently, the heat input to the air mass over an urban area requires a bias towards higher values upwind of the heat island relative to its downwind counterpart. These expectations are shown schematically in Figure 4. Some preliminary results illustrating the role of advection have been presented in Ching *et al.* (1978). Assuming that anthropogenic space heating is negligible, this spatial differential must

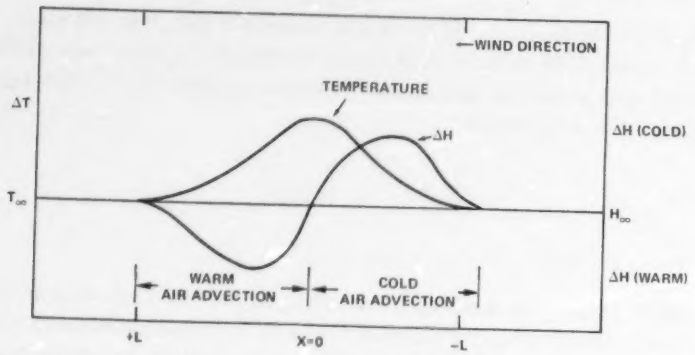

Fig. 4. Schematic of hypothetical heat island cross sections and an idealization of the heat flux anomaly, ΔH, about a non-urban heat flux H_∞ induced by advection.

be accounted for by turbulent sensible heat flux. Certainly, complex spatial distribution of anthropogenic space heating will contribute to the complexity of the urban heating pattern. Moreover, sub-urban land-use variations induce microscale temperature gradients that affect the heat anomalies associated with advection on this scale. These concepts will be explored further in the following sections.

3. RAPS Boundary-Layer Observation Program

An extensive boundary-layer field observation program was conducted in St. Louis, Missouri as part of EPA's RAPS Study. RAPS was designed to compile a complete and accurate data base for developing and validating air quality simulation models (Schiermeier, 1978). Urban boundary-layer (UBL) field studies were conducted within RAPS during the summer and fall of 1976 to document the mean and turbulent boundary-layer temperature, moisture, and wind structure, and associated air quality. The sensible heat flux was derived from these data. Further details can be found in Clarke *et al.* (1976, 1981, 1982).

The experimental design of the program provides a basis for delineating between the scales active in the urban area including bulk urban/rural differences, land-use variations, and finally the energy budgets of various surfaces within any given land-use type. The major components of this data base include: (1) concurrent instrumented tower turbulence data at three sites, (2) aircraft measurements of the turbulence structure, (3) helicopter measurements of the mixed-layer depth during morning and evening transition periods, (4) meteorological data from the Regional Air Monitoring System (RAMS) and radiosonde soundings, (5) lidar mixing heights, and (6) data from land-use energy budget studies undertaken at sites equipped with special instrumentation. The focus here will be on the use of eddy correlation measurements taken by aircraft and from towers.

Aircraft measurements were made at 150 m above ground level (AGL) and would, according to the earlier discussion, relate to a land-use fetch scale of 12–15 km. For St.

Louis, this scale should resolve the spatial variation of the urban heat island. The tower measurements made at 30 m would see 'local' land-use fetches of about 4–5 km, which are much smaller than the urban scale. The impact of advection on these measurements is discussed in detail below.

4. Results

4.1. Urban scale

Aircraft turbulence measurements were obtained over St. Louis during August 1976. The Queen Air aircraft of the National Center for Atmospheric Research (NCAR) was equipped with an inertial navigation system and a gust probe system to obtain fast-response three-dimensional wind components. These measurements, along with fast-response temperature and water vapor data, were processed to obtain heat, momentum, and moisture fluxes via the eddy correlation technique. Further experimental details can be found in Godowitch *et al.* (1981). Flight legs were designed to provide information on both horizontal and vertical urban-scale variation in the turbulent structure. The lowest level flown was at 150 m AGL. Each leg was about 70 km in length; some intersected the city while some were off to each side. All flights intersecting the central urban area at 150 m AGL, irrespective of wind direction, were used in these analyses. Each flight leg was blocked into 25-km length segments with a 15-km overlap of data from segment to segment. The heat fluxes shown in Figure 5 are normalized with the highest value observed along each of the runs. In every case the peak values were directly over or within 5 km of the urban center. The values decrease to about one-half of the peak values at distances varying between 20 to 30 km from the urban center.

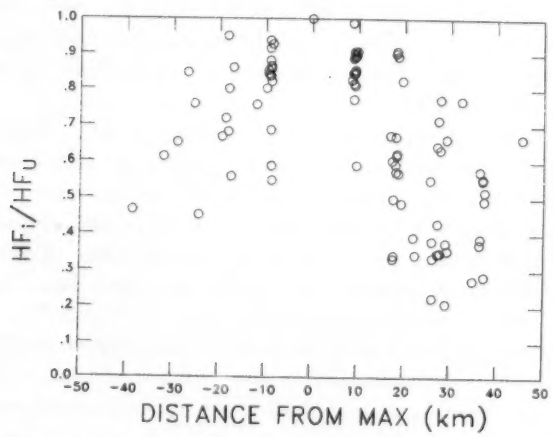

Fig. 5. Sensible heat flux at 150 m above St. Louis derived from aircraft measurements. The data are normalized by the peak values over the urban area. All flight legs intersect the downtown business district.

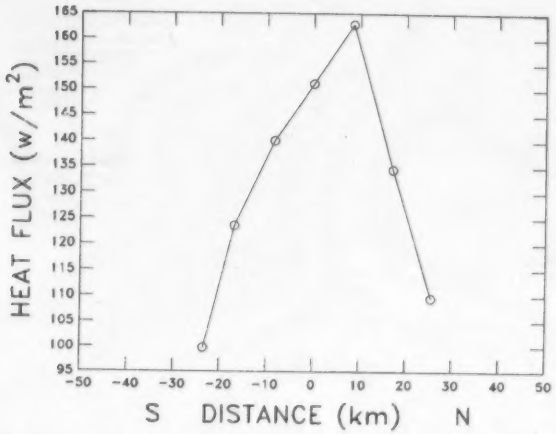

Fig. 6. Example of heat flux at 150 m over St. Louis on August 9, 1976 at 1400 CST showing the skewness of the cross-sectional distribution attributable to advection on the heat-island scale. Wind speed of 5.1 m s^{-1}, wind direction = 167° N, flight leg from S to N.

A representative profile of heat flux at 150 m across the city is shown in Figure 6. In this example, the wind from the South was parallel to the flight leg. The data indicate a skewness of higher heat flux values on the upwind segments of the run. In contrast, the heat flux values drop off rapidly on the downwind side of the urban center. These observations suggest that cold air advection upwind of the heat island center, and warm air advection beyond the heat island, influence the net heat output of the city. Further studies of this kind are desirable to substantiate these phenomena.

4.2. Sub-urban scale

A major aspect of the boundary-layer program was the study of the energy budget and turbulence structure on a scale of individual land-use areas using the eddy correlation method for heat flux, $H_0 = \rho c_p \overline{w'T'}$. This method was applied to data collected atop specially instrumented 30-m towers at RAMS sites, 105, 107, and 109 (see Figure 7) from July 20 through August 31, 1976. These three sites represent three distinctly different land-use areas. From the discussion on height of measurements based on fetch (cf. 2.1), the measurements of heat flux at 30 m can be seen to require a nominal minimum fetch of 4–5 km. A circle around each tower site (Figure 7) indicates its respective land-use domain according to this simple model. The appropriate fetch would be the upwind radius. The domains for the urban sites are slightly smaller because of a finite displacement length of 6 m at site 107 and 2 m at site 105. The displacement length for site 109 was negligible.

Site 105 was located in an industrial/commercial area of the S central section of St. Louis, approximately 3 km SSW of the urban center and 1 km W of the Mississippi River. Land surrounding the station is used for trucking, warehousing, and commercial operations. Buildings in the immediate vicinity are predominately two-story structures

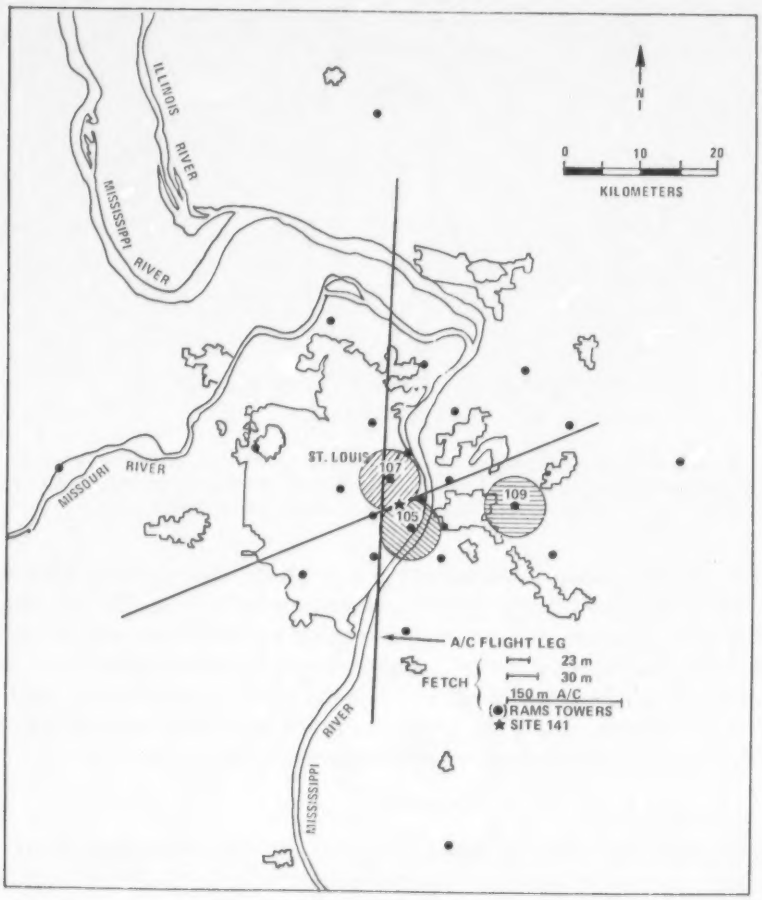

Fig. 7. Diagram of St. Louis showing the tower sites for turbulence measurements. The circles indicate the areal domain for representative heat flux measurements as derived from the model.

which together with paved area, make up about 90% of the total land use. Note that fetches from the NE through SSE will include the Mississippi River in the land use. This of course could introduce uncertainties in interpretation of the results. Special instrumentation at the site included a commercial three-axis propeller UVW anemometer and fast-response temperature system. A Lyman-alpha humidiometer was mounted on the tower from July 28 through August 7. Values from these sensors were recorded every 0.5 s in the RAMS data acquisition system. A Swisstico net radiometer was extended 2 m from the tower (near the top) and the output recorded on a Hewlett-Packard chart recorder.

Site 107 was located in the NW section of St. Louis, approximately 6 km from the center of the city. The area surrounding the site is occupied by older, single-family and

two-to-three story duplex residential dwellings. Population density is high, and the site is considered urban in character. Numerous large trees surround the dwellings. Spectral instrumentation at the site consisted of a R. M. Young UVW anemometer and a fast-response temperature system.

Site 109 was located in rural agricultural area 19 km E of St. Louis. Special instrumentation was the same as for site 105. The Lyman-alpha humidiometer was moved from site 105 to site 109 for the period of August 9–13.

These data sets were processed to obtain the mean components of three-dimensional wind, temperature, and moisture. The turbulent parts were obtained by detrending the hourly time series with a second-order polynomial of best fit. The u-component was aligned in the direction of the mean wind. Fluxes of heat, momentum, and moisture were then determined from this set of processed data. Figure 8 depicts the average diurnal

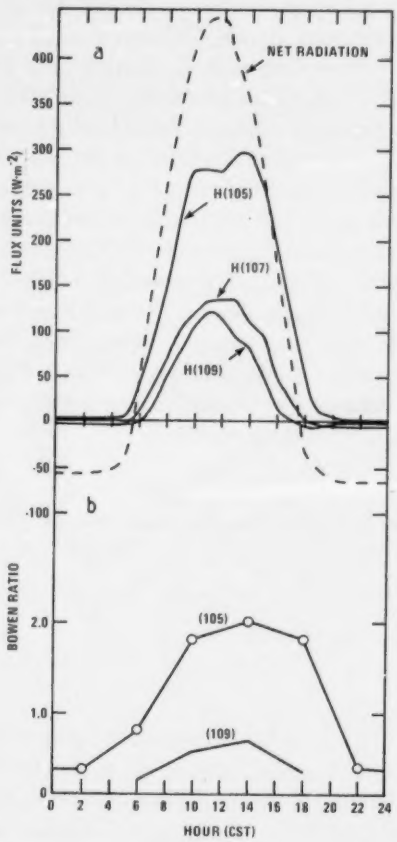

Fig. 8. Average diurnal variation of (a) H_0 for RAMS sites 105, 107, and 109 and F_n at site 105, and (b) Bowen ratio at sites 105 and 109 for August 1976 in St. Louis, MO.

variation of sensible heat flux at all three sites for the experimental period and net radiation, F_n, at site 105 derived from 12 days in August 1976. Note that a positive value for F_n represents a downward radiant flux while H, LE, and G values are positive if they are directed away from the surface. The diurnal variation of F_n for site 109 was similar to that for site 105 with the exception that nocturnal values are about 20 W/m^2 less negative. The heat flux for site 105 is significantly larger throughout the entire diurnal cycle than at either site 107 or 109. The heat flux at site 105 remains positive throughout the diurnal cycle, and peak afternoon values approach 300 W/m^2, more than half of F_n. Night-time heat fluxes at 107 and 109 are slightly negative. The magnitude of heat flux at site 105 is much larger than any value measured by the aircraft. This discrepancy reflects the greater land-use variability in heat flux than exists on the urban heat-island scale.

The net radiation and the heat flux at the rural site are in phase throughout the diurnal cycle. This constrasts with the urban data, where the heat flux lags F_n after noon. The heat fluxes exceed the net radiation at 1500 CST and 1700 CST at sites 105 and 107, respectively, and remain positive long after F_n changes sign. Thus, energy must be supplied from the subsurface to maintain this feature. At site 105, the supply of energy from the surface to the atmosphere continues throughout the night.

The surface energy budget was calculated for sites 105 and 109. The moisture flux (i.e., latent heat) component was obtained using the Lyman-alpha humidiometer data obtained for a 4-day period at site 105 followed by a subsequent 4-day period at site 109, from the one sensor available to the program. The fluxes, averaged over the period 1000 to 1300 CST, are listed in Table I. The ground heat flux, G, is the residual term of the energy budget. More than one-half of the net radiation was converted to heat flux at site 105, as indicated by the percent values in parenthesis in Table I, the remainder being divided evenly between latent, LE, and subsurface heat storage. Almost one-half of F_n at site 109 went to evaporate water, while about one-third went to sensible heat flux, and about one-sixth went to the ground.

TABLE I

Average energy budget components (1000–1300 CST) (W m^{-2})

Site	F_n	H	(%)	LE	(%)	G	(%)
105 (urban)	473	244	(52)	115	(24)	115	(24)
109 (rural)	464	171	(37)	221	(48)	72	(16)

The Bowen ratio, BR = H/LE, is also presented in Figure 8. Daytime values varied around 2 at urban site 105, while averaging about 0.7 at site 109. Sisterson (1975) using Metromex data (also for St. Louis) reported average urban-area Bowen ratios of 2.9 and 2.0, while obtaining 1.0 and 0.8 for the average rural values for two case study periods. Maisel (1971) found the sensible heat flux to be 2.7 times greater for an asphalt parking lot compared to a weed field, in a developing suburban-industrial community. Oke

(1974) concluded that the latent heat flux could be much smaller than the sensible heat flux for land uses composed of a large fraction of impervious surfaces. Thus, Bowen ratio data obtained in the present study are consistent with the results of previous investigators, and are also consistent with the high heat flux values obtained for site 105.

Site 107 is characteristically urban; however, the sensible heat flux was much smaller than at site 105. A plausible explanation is that evapotranspiration was very active at this site during the observational period. Vegetation consisted primarily of trees and shrubs and comprised more than one-half the surface area at site 107. This contrasts sharply with the approximately 10% or less of vegetated surface at site 105. Therefore, conditions were favorable for high latent heat flux output at site 107, in contrast to site 105, explaining the intra-urban land-use differences of sensible heat flux. Unfortunately, moisture flux data were not taken at site 107 to verify the hypothesis.

A second boundary-layer study similar to that described above for the summer period was conducted in St. Louis from October 20 through November 15, 1976. Neither net radiation nor moisture fluctuation data were available during this period. The diurnal variation of the heat flux for this data base is shown in Figure 9. A comparison of these

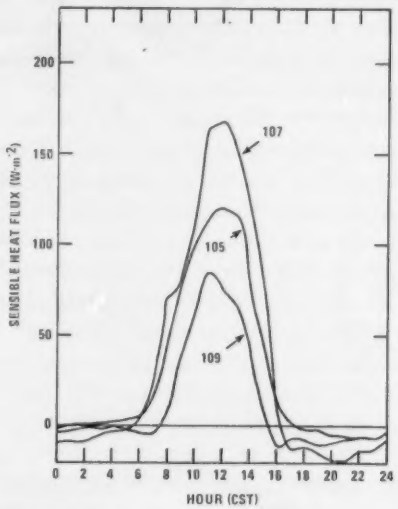

Fig. 9. Average diurnal variation for H_0 for RAMS sites 105, 107, and 109 for October/November 1976 in St. Louis, MO.

diurnal variations against those of the summer period (Figure 8) show that peak heat flux values at sites 105 and 109 are reduced by a factor of 2.5 and 1.5, respectively, and increased by 25% at site 107. These results are not inconsistent with changes that might reasonably be expected at the various sites. While F_n is expected to decrease in the fall, the evapotranspiration processes also should decrease significantly and anthropogenic heating should increase at the urban sites. The increase in sensible heat flux at site 107 must reflect a very large decrease in LE. An analysis of space heating requirements

showed a small increase of midday values from 23 to 31 W/m^2 in October compared to July at site 107. At site 105, the space heating midday values increased from 29 to 33 W/m^2 in October. Thus, the decrease in net radiation is reflected in the decrease in sensible heat since latent heat was generally not significant. In addition, site 105 is now downwind of the urban center since the prevailing wind direction was from the NW where warm air advection effects might be significant. This feature is discussed below in more detail. The decrease of sensible heat flux at site 109 is attributed primarily to the seasonal decrease in net radiation.

5. Discussion

Advection within a heat island must play a role in inducing the spatial distribution of heat flux across the city as discussed previously. The data from Figure 6 illustrate this feature on the urban scale. This process should also influence the heat flux on the local land-use scale. The results discussed below analyze this effect from the tower measurements.

The St. Louis heat island is generally located to the West of the major downtown central business district. Thus site 105 can be considered to be on the upwind side of the heat-island center for winds from the NNE to S and downwind for winds from the WNW to N. Moreover, this influence is expected to be enhanced by wind flow over the relatively cool Mississippi River. Site 107 appears to be located near the center of the heat island, and site 109 may be far enough away to escape the influence of the heat island. Data from both the summer and fall measurement periods were analyzed to determine if advection could modulate the amount of sensible heat released at any site. Since site 107 is in the vicinity of the heat-island center, its heat flux should not be strongly influenced by advection. Since site 105 would be upwind (downwind) of this heat island for wind directions from the SE (NW), one would expect cold air advection to influence this site with SE flow and warm air advection with NW flow.

The directional dependence of heat flux for each of the three sites is shown in Figure 10. These data are limited to the time period between 0900 and 1700 CST. The most striking feature is the large heat flux values at site 105 in the wind direction sector from the NNE, clockwise to SSE, relative to values for air flow from the western, more urban sectors. Some values in the eastern sector were comparable to the average net radiation magnitude shown in Figure 8. For winds from the eastern sector, the urban heat-island cold air advection effect is probably enhanced by the land-water (i.e., Mississippi River) temperature contrast; winds from the W through N may induce a supression of sensible heat flux due to warm air advection downwind of the urban heat-island center. The results for site 107 do not indicate as large a directional anomaly. However, there appears to be a positive bias in the western sector from SSW through to NNW with peak anomaly in the WNW direction. The response at site 107 for wind directions from the NNW extending clockwise through the S was relatively a flat minimum. Since site 107 is very near the center of the heat island, assessing whether the observed directional anomaly is due to cold air advection for the westerly directions or to warm air advection

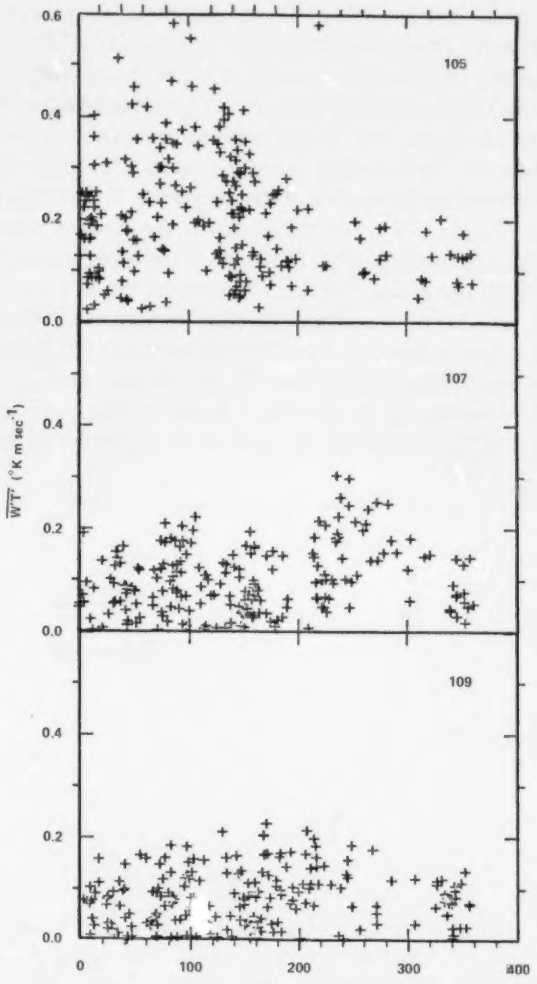

Fig. 10. Directional dependence of heat flux at tower sites 105, 107 and 109 for 20° direction classes derived from the summer 1976 RAPS observation period.

from the eastern half is a difficult task. Quite possibly, this anomaly may be associated with local land-use gradients (i.e., cold and warm spots). The results for the rural site (109) do not indicate any significant directional anomaly. Evidently, the influence of warm air advection on the heat flux at this site is insignificant compared to its local land-use control.

The largest difference between heat fluxes at site 105 and site 107 appears in the sector having an approximate mean of 110°. Interestingly, the magnitude of the difference is about three times as large as the magnitude of the heat flux at site 107. In contrast, the

magnitudes of the heat flux at sites 105 and 107 are about equal for winds from the west. We believe that advective effects could dominate the spatial variability of heat flux measurements, especially in sub-urban or land-use scales. To examine the differences between sites 107 and 105, the data from each of the sites are referenced simultaneously to the values measured at site 109. In this way, the synoptic variability from the directional biases between the two urban sites is reduced. This approach, of course, assumes that urban advective effects at site 109 are negligible. The average ratios of heat fluxes normalized to the site 109 values are plotted as functions of wind direction in Figure 11. These data are averages over 20 deg wind direction sectors. The features observed in Figure 10 clearly remain. The heat output at site 105, however, is about three to four times that at site 109 with winds from the eastern sector, and it decreases almost two-fold when the air flow is from the west. Heat fluxes at site 107 are comparable to those at site 109, except perhaps with winds directly from the west.

A simple test of the significance of advection induced by local and heat-island-scale thermal patterns in modulating the heat flux can be accomplished by first defining a

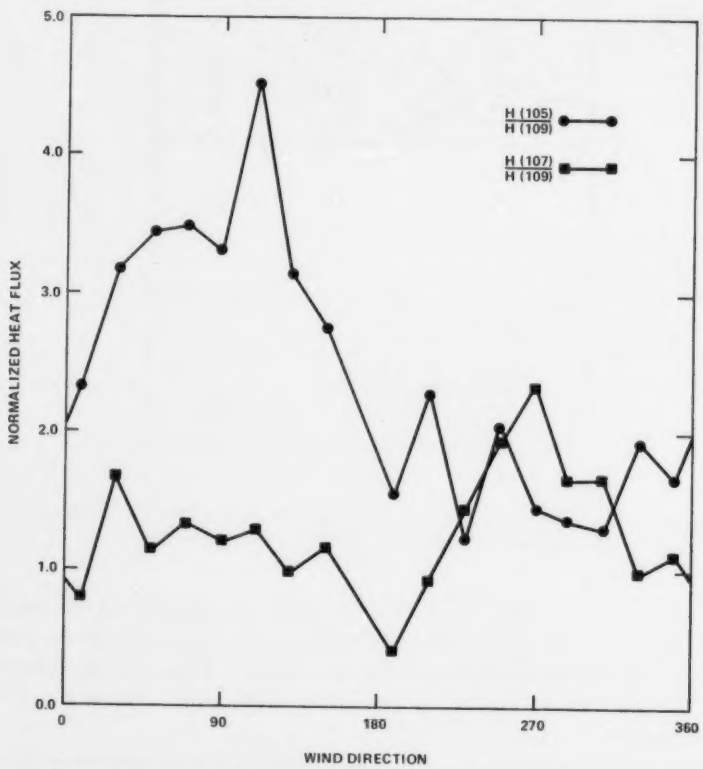

Fig. 11. Directional dependence of average heat flux normalized by the values at rural site 109 for 20° direction classes for summer 1976 observation period.

variable $A = (H_{105} - H_{107})/H$ where H is the average value of the heat flux measured concurrently at both sites, 105 and 107. The normalizing factor, H, is designed to filter the diurnal variability for this analysis. Means and variances of A are computed for wind direction classes with fetch over the Mississippi River (45°–210°) and for the NW flow (270°–330°). The means of these classes of flows can be considered to be along the axis between sites 107 and 105. Thus, winds from the NE through SSW sector will place 105 under cold air advection primarily from the relatively cold River and augmented by the heat-island gradients. NW flows will either impact site 107 as cold advection or site 105 as warm air advection due to heat island gradients, although the gradients are not as large as from the SE. Winds from the other remaining directions will be broadside to the 105–107 axis and consequently the differential thermal gradient between the two sites is expected to be negligible. The mean of this class of flows can be considered and designated as reference. The significance of the difference of the means between the along-axis flow and the reference or cross-axis flow was computed separately for both the summer and the autumn data using the Student T distribution. Note that such a comparison serves to filter out the land-use variability between site 105 and 107. The data were screened to require all heat flux values to be positive, at least 10 W/m^2, and wind speeds greater than 2 m s^{-1}. The differences between the means were both positive and highly significant with summer winds from off the River sector with a probability greater than 0.999 for 124 deg of freedom. We know from aircraft over-flights that surface radiometric temperatures over the River were about 25 °C colder than the comparable land temperature at site 105. This strongly suggests that it is cold advection that sets up the high heat flux values at site 105. No data were available to test the hypothesis for the north-west class in the summer. The data for the Fall period did not demonstrate any significant difference in the means for either the southeast or the northwest tests. Over-river fetches in the Fall are not expected to be large simply because the temperature difference between the River and the adjacent land is expected to be much smaller than in the summer. The statistical test is consistent with this hypothesis. On the other hand, the analysis indicates only about a one-in-four or -five chance that the class mean for the NW flow is the same as that for the reference class with 59 degrees of freedom. This result, while not to be accepted as significant, provides a limited indication that heat flux is enhanced at site 107 relative to that of site 105 as would have been anticipated.

Figure 12 shows the correlation between W and T, $r_{wT} = \overline{w'T'}/\sigma_w\sigma_T$ plotted as a function of wind direction. Again the largest values are for site 105 for winds off the Mississippi River. These values varied about a factor of two higher than for the corresponding wind directions at either site 107 of 109. The values at all three sites were comparable for other wind directions. This suggests that air-flow off the Mississippi River must be more organized on the sub-urban mesoscale; the circulation permits an enhanced vertical transport of heat.

Now consider the vertical extent of the advective influence on heat flux output resulting from thermal anomalies varying in scale from the large urban scale (as shown in Figure 4) to the local land-use scale, as found, for example, in land-river contrasts

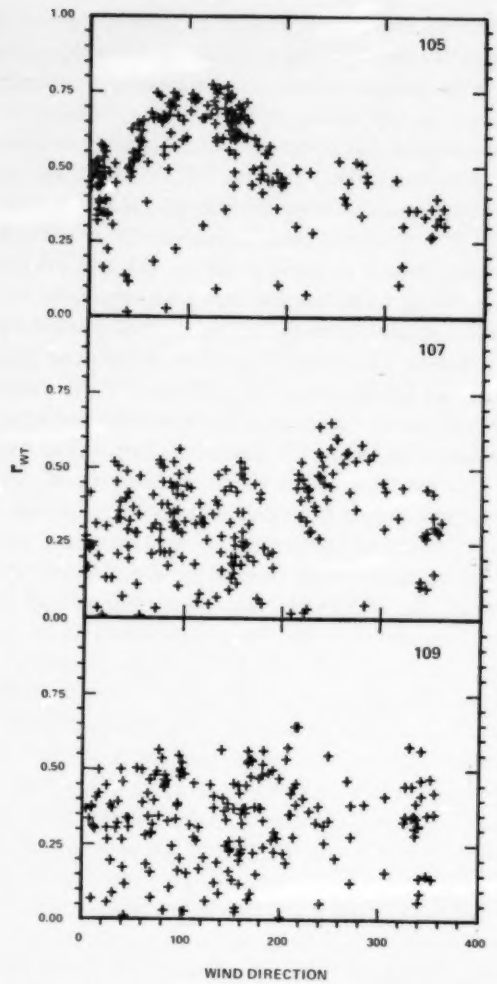

Fig. 12. Direction dependence of correlation coefficient r_{wT} at tower sites, 105, 107 and 109 derived from the summer 1976 RAPS observation period.

or differences due to lakes, industrial and recreational parks, and shopping centers. Using the following simplified analyses, one can integrate the enthalpy budget (see Equation (7)) for these anomalies to obtain:

$$D_L = \frac{\lambda_L \delta H_L}{S_L \overline{\Delta T}_{xL}} \tag{8a}$$

and

$$D_u = \frac{\lambda_u \delta H_u}{2\pi S_u \overline{\Delta T}_{xv}} \tag{8b}$$

TABLE II

Typical values and range of parameters measured

Scale	Shallow	Typical	Deep
Local Land Use			
S (m s^{-1})	5	2	1
ΔT_x (°C)	2	1	2
λ (km)	1	2	4
ΔH (°m s^{-1})	0.2	0.15	0.2
D_L (m)	20	150	200
Urban Heat Island			
S (m s^{-1})	5	2	2
ΔT_x (°C)	2	0.5	0.2
λ (km)	20	50	50
ΔH (°m s^{-1})	0.1	0.1	0.1
D_u (m)	30	800	2000

where D_L and D_u are the depths of advective influences on heat flux from local land-use scales and urban heat-island scales, respectively. Hence λ represents the length scale, S is the layer-averaged wind speed, and $\overline{\Delta T_x}$ is the layer-averaged horizontal temperature difference. The subscripts L and u refer to local land-use and urban heat-island scales respectively. δH is the excess heat flux induced by the thermal anomaly. Table II shows typical values and a realistic range of these various parameters. This analysis indicates that the depth of influence is proportional to the scale of the phenomena or inversely proportional to the temperature gradients. For example, D_L is about one order of magnitude smaller than D_u which is on the order of or somewhat less than the height of the mixed layer. Thus, the local land-use perturbation is limited to a very shallow layer and may not be very evident in measurements made at great altitudes. The normal range of parameter variations permits a large range in D; conversely, one can expect a large range in H. This is certainly evident in the case of the heat flux variations observed at site 105 where the advective anomaly is largest.

6. Summary and Conclusions

Heat flux in an urban area varies with land use, its composition, areal extent, and spatial distribution, and is subject to advective influences on scales varying from urban to sub-urban land use. A methodology is proposed to evaluate the sampling height requirement to obtain a representative measurement of a land-use area of interest. The method incorporates measurement results for the scale of heat-bearing eddies in a convective boundary layer obtained from experiments in Minnesota (see Caughey and Kaimal, 1977) and recast to obtain a similarity relationship for the covariance scales as a function of z/h. This result along with appropriate statistical arguments provides the basis for the proposed model. It is recognized, however, that this model incorporates data collected over uniform and ideal conditions, unlike those typical of the urban environ-

ment. The validity of the similarity relationship should therefore be further investigated to provide a more realistic model for heat flux measurements in urban (and other non-homogeneous) environments. Therefore, the methodology adapted here must be considered preliminary.

The second major emphasis of this research deals with thermal advection and the heat anomalies that are induced as a result of contrasting thermal gradients. There is clearly a theoretical basis and observational evidence to indicate that the magnitude of this effect is not insignificant, and in fact, can even dominate the variability observed. The location of a measurement site with respect to both the heat island center and other land-use patterns will exert a large, and under certain circumstances dominant control of the sensible heat flux output of a given site. It is also suggested that there is a definite relationship between the depth of the layer of advective influence and the horizontal scale of interest. Variations on the scales of the heat island are modulated by advection to a depth of about one-half or more of the mixed layer height. In contrast, pronounced temperature gradients on smaller land-use scales are limited to very shallow layers.

The diurnal, seasonal and spatial variability of heat flux for two different urban sites and one rural land-use site was assessed. Large differences in heat fluxes exist between the various land uses, and between the summer and fall seasons. More importantly, the data indicate that advection plays a dominant role in modulating the heat flux on the sub-urban scale and may also be significant on the urban scale. It follows that large spatial variations in the heat flux will be a characteristic of any urban boundary layer. Moreover, this variability should be directly related to enhanced dispersion potentials as reported for example in Clarke *et al.* (1981). The impact of large spatial variability of heat flux on plume spread is explored in Carlson *et al.* (1980).

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